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1)10397890 99408239 PMID: 10480362
Genomic organisation of the human chordin gene and mutation screening of candidate *Cornelia* *de* *Lange* syndrome genes. Smith M; Herrell S; Lusher M; Lako L; Simpson C; Wiestner A; Skoda R; Ireland M; Strachan T
Human Molecular Genetics Unit, School of Biochemistry and Genetics, University of Newcastle upon Tyne, UK.
Human genetics (GERMANY) Jul-Aug 1999, 105 (1-2) p104-11, ISSN 0340-6717 Journal Code: 7613873
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We have determined the genomic organisation of the

2) *Fetal* *hemoglobin* *induction* with butyric acid: efficacy and toxicity.
Blau C A; Constantoulakis P; Shaw C M; Stamatoyannopoulos G Division of Medical Oncology, University of Washington, Seattle. Blood (UNITED STATES) Jan 15 1993, 81 (2) p529-37, ISSN 0006-4971 Journal Code: 7603509
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Butyric acid *induces* *fetal* *hemoglobin* (HbF), a property of potential therapeutic advantage in patients with disorders of globin chain synthesis. We performed dose escalation studies of this compound in baboons to

3) Stimulation of *fetal* *hemoglobin* production by short chain fatty acids.
Liakopoulou E; Blau C A; Li Q; Josephson B; Wolf J A; Fournarakis B; Raisys V; Dover G; Papayannopoulou T; Stamatoyannopoulos G
Department of Medicine, University of Washington, Seattle. Blood (UNITED STATES) Oct 15 1995, 86 (8) p3227-35, ISSN 0006-4971 Journal Code: 7603509
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Fetal Hemoglobin Induction With Butyric Acid: Efficacy and Toxicity

By C. Anthony Blau, Pantelis Constantoulakis, C.M. Shaw, and G. Stamatoyannopoulos

Butyric acid induces fetal hemoglobin (HbF), a property of potential therapeutic advantage in patients with disorders of globin chain synthesis. We performed dose escalation studies of this compound in baboons to assess whether clinically significant increases in HbF are achievable, and to define the associated toxicities. Additionally, the effect of butyrate in combination with erythropoietin on HbF induction was assessed. HbF induction in response to butyrate was dependent on the dose and duration of treatment. Doses of butyrate less than 4 g/kg/d were associated with minimal toxicity (hypokalemia) and significant HbF induction in these nonanemic animals, with 1 g/kg/d producing an increase in HbF-containing reticulocytes (F reticulocytes) from 0.9% to 8.7% and an increase in HbF from 0.8% to 1.4%. A dose of 2 g/kg/d resulted in an increase in F reticulocytes from 2.1% to 27.8% and an increase in HbF from 0.7% to 2.2%. Doses of 4 g/kg/d in another animal produced an increase in F reticulocytes from 1% to 21.6% and in HbF from 1.9% to 5.3%. Infusions in excess of 4 g/kg/d were complicat d (after a variable amount of time) by a decreased level of al rtness (caused by hyperosmolality or butyrate itself) and hematologic toxicity (with declin s in reticul - cyt , white blood cell, and platel t counts). Prolonged infusions of high doses of butyrate (8 to 10 g/kg/d) were associated with peak F reticulocyte percentages reaching 38% to 64.5% and HbF reaching levels in excess of 20%. These high doses (8 to 10 g/kg/d) were complicated in tw animals with a striking and unique neuropathologic pictur and, in one animal, multiorgan system failure. Erythropoietin in combination with butyrate, induced F reticulocytosis in an additive manner. We conclude that butyric acid is a strong inducer of HbF, particularly when administered in combination with erythropoietin. As chronic toxicities r - main undefined, patients in future clinical trials of this and similar compounds should be monitored closely for evidenc of neurologic toxicity.

INDUCTION OF fetal hemoglobin (HbF) synthesis is a property common to many candidate drugs for disorders of globin chain production. Which, if any, of these compounds will emerge to become a standard part of treatment for patients with sickle cell disease or β-thalassemia depends in large part on a determination of therapeutic index. Butyric acid or the structurally related compound, α-amino–butyric acid (ABA), have been shown to induce HbF in cultures of adult blood,[1] induce embryonic globin expression in azacytidine-treated adult chickens,[2] retard the switch to adult globin synthesis in sheep fetuses,[3] and stimulate HbF production when administered to adult primates.[4,5]

We have performed dose escalation studies of butyrate in adult primates to (1) define toxicities that occur at various doses of butyrate, and (2) determine the extent of HbF induction at each dose. In addition, we have evaluated the effect of butyrate when administered in combination with another inducer of HbF, erythropoietin (Epo).

MATERIALS AND METHODS

Animals. Five healthy juvenile baboons (*Papio cynocephalus*), housed and cared for at the University of Washington Regional Primate Center, were used for this study. Femoral vein catheters were placed before beginning drug administration. Butyric acid, 99% pure (purchased initially from JT Baker [Phillipsburg, NJ] and later from Aldrich Chemical Co [Milwaukee, WI]), was titrated with a 50% sodium hydroxide solution (JT Baker) or arginine powder (Sigma Chemical Co, St Louis, MO) to pH 7.2 to 7.4. The solution was then sterilized by passage through a 0.22 μL Millipore filter (Bedford, MA), diluted in 500 to 1,000 mL bags of sterile water (with or without 5% dextrose), and administered as a continuous intravenous infusion. Human recombinant Epo was generously provided by Genetics Institute (Boston, MA) and was administered in two divided doses via intermittent intravenous boluses thrice weekly. All animals received iron supplementation (iron dextran 100 mg), vitamin B12 (100 mg), and folic acid (5 mg) intramuscularly every week.

Hematologic studies. Determinations of levels of Hb, hematocrit, red blood cells (RBC), white blood cells (WBC), and platelets were made using standard methodology. Proportions of reticulocytes were calculated by counting 1,000 cells. The proportion of HbF-containing reticulocytes (F reticulocytes) was evaluated using a previously described method.[6] In brief, the reticulum was first precipitated by incubating blood with 1% brilliant cresyl blue (BCB); smears were prepared, fixed in methanol, and labeled with an anti-γ–chain monoclonal antibody and antimouse F(ab')$_2$-fluorescein isothiocyanate (FITC) in the presence of 0.005% acridine orange. With this method, the precipitated reticulum appears red-orange; reticulocytes that do not contain HbF show the red-orange reticulum on a black background, whereas F reticulocytes have a green background. The preparations were viewed in a Zeiss Universal fluorescent microscope (Thornwood, NY) equipped with epiilumination and a 200-mercury/150-xenon power source. HbF was quantified by alkaline denaturation as described previously.[7]

Other studies. Laboratory evaluation in all animals (except animal A, Table 1) included levels of serum electrolytes, glucose, blood urea nitrogen (BUN), creatnine, glucose, prothrombin time (PT), partial thromboplastin time (PTT), alkaline phosphatase, aspartate aminotransferase (AST), alanine aminotransferase (ALT), bilirubin, lactate dehydrogenase (LDH), albumin, and amylase. These were obtained at baseline and either weekly (treatment courses 2 and 5, Table 1) or with the development of clinical toxicity. Additional laboratory evaluations obtained in some animals included total cholesterol, low-density lipoproteins (LDL), high-density lipoproteins (HDL), triglycerides, insulin levels, creatine phosphokinase (CPK), fibrinogen, osmolality, ammonia, and coagulation factor activity levels.

RESULTS

Table 1 outlines the doses and durations of seven courses of butyrate administration in five different animals. Doses of

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Table 1. Summary of Experiments

Animal	Treatment Course	Butyrate Dose (g/kg/d)	Duration (d)	Maximal % F Reticulocytes
A	1	1	35	8.7
		2	25	27.8
B	2	2	8, 16*	6.2
	3	4	3	NA
C	4	4	27	21.6
		8	16	38
	5	2	16	6.7
		3	22	9.5
		8	29	64.5
D	6	8	3	NA
E	7	10	1.5	NA

Summary of doses and durations of butyrate infusions, and peak F reticulocyte responses. Sodium butyrate was used in treatment courses 1 to 6, and arginine butyrate was used in course 7. All treatments were administered by continuous intravenous infusion, and except in experiment 4, all dose increases were separated by at least 2 days.

Abbreviation: NA, not applicable because of the short duration of treatment.

* On day 8 of treatment course 2, butyrate was interrupted for 10 days due to catheter malfunction.

butyrate ranged between 1 and 10 g/kg/d. Sodium butyrate (NaB) was used in treatment courses 1 through 6, and arginine butyrate was used in course 7.

HbF Induction

NaB at a dose of 1 g/kg/d produced an increase in F reticulocytes from 0.9% to 8.7% (Fig 1). An increase in dose to 2 g/kg/d resulted in a further increase to 25% F reticulocytes. F cells increased from 4% to 6.7% with the 1 g/kg/d dose, and reached 15.2% with 2 g/kg/d. HbF increased from a baseline of 0.8% to 1.4% with 1 g/kg/d of butyrate, and increased further to a maximum of 2.2% with 2 g/kg/d. The response observed in animal B (Table 1) to 2 g/kg/d was less pronounced, with an increase in F reticulocytes from 0.8% to 6.2% and no discernible increase in HbF. The responses to higher doses of butyrate were studied in treatment courses 3 through 7 (Table 1 and Fig 1). As outlined in Table 1, animal C was treated with two prolonged courses of NaB. In the first course, NaB administration at a dose of 4 g/kg/d for nearly 4 weeks was followed uninterrupted by treatment for an additional 16 days at 8 g/kg/d. At 4 g/kg/d, F reticulocytes increased from 1% to 21.6%, F cells increased from 5.4% to 14.3%, and HbF climbed from 1.9% to 5.2%. At 8 g/kg/d, F reticulocytes, F cells, and HbF further increased to 38%, 36%, and 16.5%, respectively. In a second set of infusions (Fig 1), beginning at 2 g/kg/d for 2 weeks, F reticulocytes increased from 2.4% to 6.7%, F cells increased from 6.9% to 11.2%, and HbF changed very little (3.2% to 3.8%). At 3 g/kg/d, F reticulocytes further increased to 10.4%, F cells went to 21.8%, and HbF increased to 5.7%. With a final escalation in dose to 8 g/kg/d, F reticulocytes peaked at 65%, F cells reached 37%, and HbF attained 20.8%. In the three animals that received 4 to 10 g/kg/d of butyrate for less than 72 hours because of the development of toxicity (courses 3, 6, and 7 of Table 1), no significant change in any parameter of HbF induction was observed (data not shown).

Sodium butyrate and erythropoietin induce HbF additively. One animal that had completed treatment with NaB alone (animal A) was treated with intravenous Epo (2,000 U/kg in 2 divided doses) thrice weekly for nearly 4 weeks, to which NaB was then added. Figure 2 shows the response to NaB alone (transposed from Figure 1), Epo alone, and NaB in combination with Epo. As stated previously, with NaB alone at a dose of 1 g/kg/d, F reticulocytes, F cells, and HbF increased to 8.7%, 6.7%, and 1.4%, respectively. With 2 g/kg/d, these increased further (in the same order) to 25%, 15.2%, and 2.2%. With Epo alone, F reticulocytes increased from 0.9% to 15%, F cells increased from 3% to 5.7%, and HbF climbed from 1.1% to 2.2%. Of note is that HbF had not yet appeared to stabilize at the time NaB was added to Epo (Fig 2). NaB was added at 1 g/kg/d in combination with continued Epo for an additional 40 days. F reticulocytes increased to 23%, F cells increased to 13%, and HbF increased to 3.9%. With a further increase in NaB to 2 g/kg/d for an additional 30 days, F reticulocytes increased to 40%, F cells increased to 25%, and HbF reached 9%. These results suggest that NaB augments HbF in an additive fashion when administered in combination with Epo.

Toxicities

In five of the seven courses, infusions were discontinued because of the development of obtundation (Table 2). Three animals died (C, D, and E), one during parenteral administration of potassium for hypokalemia with a presumed arrythmia (animal C, treatment course 5), a second (animal E) following the development of multiorgan system failure within 36 hours after starting the highest administered dose of butyrate (10 g/kg/d), and the third (animal D) in a control experiment in which hypertonic solutions (without butyrate) were used to produce hyperosmolality.

Electrolytes. Hyperosmolality (calculated or measured serum osmolality >300 mOsm/L) was noted during six courses of butyrate administration (Table 2, courses 2 through 7). In courses 2 through 6 (in which NaB was used), hypernatremia was the predominant contributor to hyperosmolality. In course 7, in which arginine butyrate was used instead of NaB, the serum sodium concentration was markedly low (114 mEq/L), and the major contributors to hyperosmolality were unmeasured compounds (presumably arginine, butyrate, or metabolites of these compounds), with a difference between measured and calculated osmolality (osmolar gap) of 68 mOsm/L (normal for humans is <10 mOsm/L).

Hypokalemia occurred during five courses of butyrate administration (Table 2, courses 2 through 6). Its severity appeared to correlate with dose and was, at times, accompanied by an elevated serum bicarbonate concentration, presumably a metabolic product of butyrate. Moderate hypocalcemia and hypomagnesemia occurred only in the animal (Table 2, animal E) receiving the highest dose of butyrate.

Hematologic toxicity. Reticulocytes and platelets decreased in a dose-dependent fashion as shown in Fig 3. Leukocyte counts closely mirrored these changes (data not shown). Whereas no decrease in reticulocytes occurred at

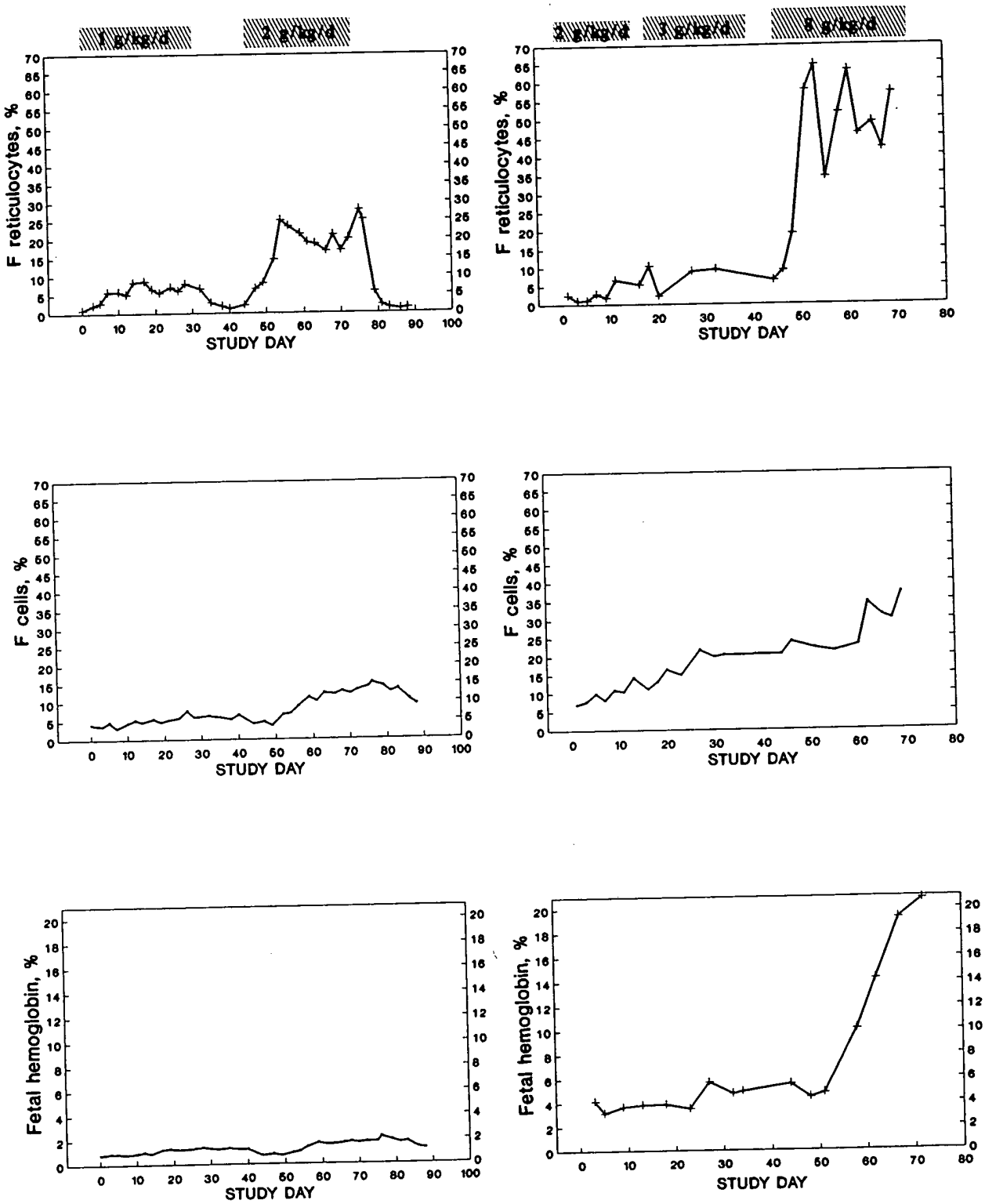

Fig 1. HbF induction in response to escalating doses of NaB. Data from animal A are shown on the left, and animal C on the right. Doses of NaB are shown in shaded rectangles above.

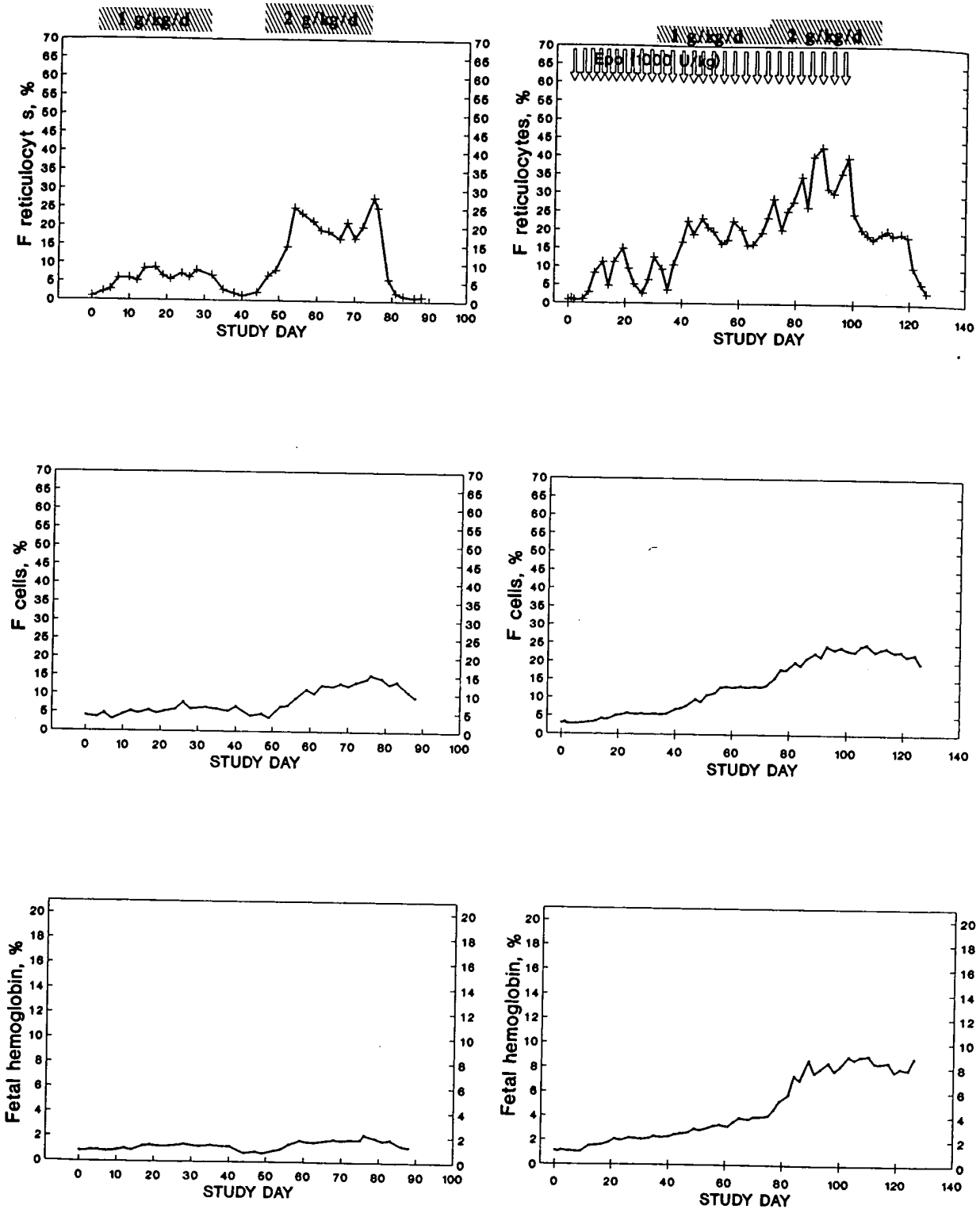

Fig 2. HbF induction in animal A in response to butyrate alone (left, transposed from Fig 1), Epo alone, and Epo in combination with butyrate (right). Epo (1,000 U/kg) was administered intravenously thrice weekly. Individual doses of Epo are designated by vertical arrows. Doses of NaB are shown in shaded rectangles. These data suggest that Epo and NaB augment HbF additively.

Table 2. Treatment Toxicity

Animal	Treatment Course	Butyrate Dose (g/kg/d)	Toxicities	Peak Osmolality (mOsm/L)
A	1	1	None detected	Not done
		2	None detected	Not done
B	2	2	Hypokalemia*	319†
	3	4	Obtundation	321†
C	4	4	None detected	319†
		8	Hypokalemia, obtundation, diarrhea, hematologic, cerebellar ataxia	337†
	5	2	Hypokalemia*	317†
		3		310†
		8	Hematologic, obtundation	315
D	6	8	Hypokalemia, obtundation	360
E	7	10	Multiple	351

Summary of toxicities and peak osmolalities with each dose or butyrate.

* Calculated serum osmolality. Other values are measured.

† Hypokalemia at lower doses persisted at higher doses in the same animal. Hematologic toxicity includes coagulopathy, anemia, leukopenia, or thrombocytopenia.

doses of butyrate up to 2 g/kg/d, declines were observed at doses of 3 to 4 g/kg/d. Reticulocytopenia persisted despite significant decreases in the hematocrit in courses 5 and 7 (Fig 2 and data not shown). The mean corpuscular volumes (MCV) did not significantly change. Platelet counts decreased slightly at 2 g/kg/d, and decreased more significantly at higher doses. A profound decrease in hematocrit occurred in concert with multiorgan system failure in animal E (Table 1), in which, over 2 days, the hematocrit decreased from 40% to 23%. Evidence of hemolysis included an abrupt elevation in serum lactate dehydrogenase (to 7,780 U/L), undetectable haptoglobin, and a serum-free hemoglobin of 6 mg/dL. More gradually progressive anemia developed during prolonged butyrate infusions at doses of 8 g/kg/d (Fig 1 and data not shown), and occurred in the absence of apparent blood loss or abrupt hemolysis.

Also in animal E, which received arginine butyrate at 10 g/kg/d, a fulminant coagulopathy developed within 33 hours of starting the infusion, with a PT of 31.3 seconds (2.61 times mean), activated PTT of 71 seconds (2.54 times mean), fibrin degradation products (FDP) greater than 1,000 ng/mL, and a fibrinogen of 60 mg/mL. Surprisingly, the platelet count remained stable at 436,000/μL. Further evaluation showed the following coagulation factor activities: X, 8%; V, 21%; VII, 30%; and VIII, 107%. A diffuse petechial eruption was noted in the hours preceeding death. In animal C, which received butyrate at 8 g/kg/d for 29 days (Table 2, course 5), epistaxis developed; the PTT was elevated at 44 seconds (1.6 times mean) with FDP between 200 and 500 ng/mL. PT, fibrinogen levels, and platelet levels were normal in this animal.

Neurologic toxicity. A diminished level of consciousness complicated butyrate administration in five of the seven treatment courses (Table 1). The dose of butyrate at which this occurred varied between animals, with animal B developing obtundation within 3 days after beginning a butyrate infusion at 4 g/kg/d, and animal C not showing apparent changes in alertness until 2.5 and 4 weeks of treatment at 8 g/kg/d (courses 4 and 5, respectively, Table 2). We are unable to distinguish whether this complication is attributable to butyrate itself, its metabolites, or other factors such as hyperosmolality. With most treatments, these changes were rapidly reversible with discontinuation of the infusion, the only exceptions being animals C and E.

Animal C received two courses of NaB (Table 2 and Fig 2). In the first course, NaB was administered at a dose of 4 g/kg/d for nearly 4 weeks followed uninterruptedly by an increase in dose to 8 g/kg/d. Three days before the discontinuation of treatment, ammonium butyrate was substituted for NaB. The infusion was discontinued when the animal was noted to rapidly become lethargic. The calculated serum osmolality was 329 mOsm/L (increased from a baseline value of 319 mOsm/L), and serum ammonia level and BUN were normal. The animal's level of consciousness improved noticeably within 12 hours after discontinuation of the drug, despite an increase in the calculated serum osmolality to 332 mOsm/L. However, the animal was found to have a striking cerebellar ataxia that appeared to gradually and completely resolve over a period of 8 weeks. This animal was subsequently retreated with escalating doses of sodium butyrate (Table 2), before again developing obtundation after nearly 10 weeks of treatment, with 4 weeks of treatment at a dose of 8 g/kg/d. There was no evidence of ataxia, and the animal died abruptly 12 hours after discontinuation of the infusion of a probable arrythmia.

Animal E received 10 g/kg/d of arginine butyrate for 8 hours before the infusion was interrupted because of technical error. The following day butyrate was resumed, but was again discontinued after 10 hours (33 hours after it was first started) because of the development of obtundation. The animal developed multiorgan system failure (see below) and was killed 30 hours later.

Other toxicities. Animal E developed elevated transaminases, acute renal failure, hyperglycemia, hypoalbuminemia, and an elevated amylase before death. In other animals, only modest (<twofold) elevations in transaminases were observed. Diarrhea was noted in animals C and E just before interruption of the infusion.

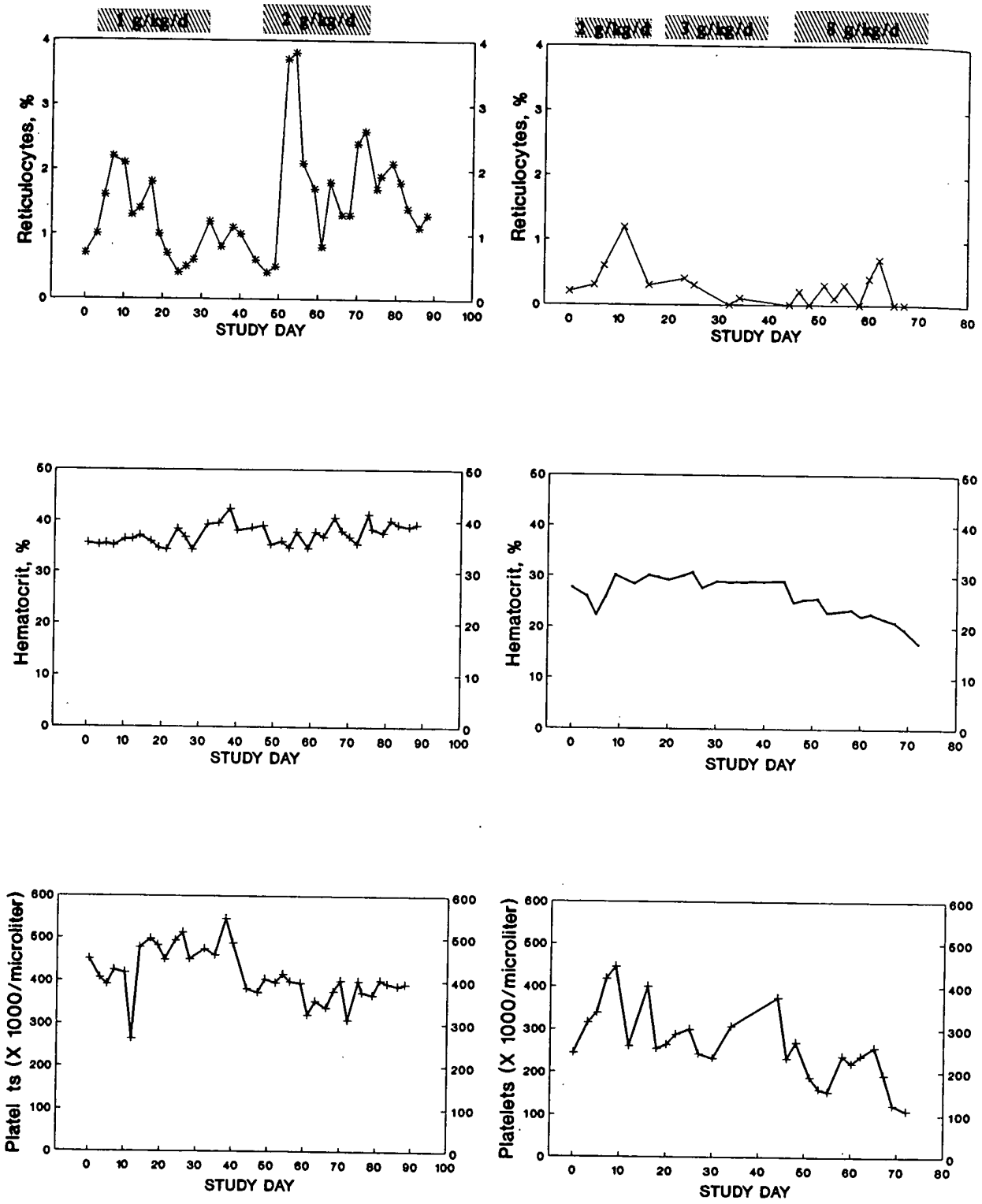

Fig 3. Changes in percent reticulocytes, hematocrit, and platelets in response to increasing doses of NaB. Results from animal A are shown on the left, and animal C on the right. Doses of NaB are shown in shaded rectangles above.

Pathology. Neuropathologic examination in animal C, which had developed cerebellar ataxia 5 months before death, showed cystic necrosis within the dentate nuclei bilaterally (Fig 4A). On microscopic examination, approximately one-third of the lesion was cystic, and the remaining two-thirds contained macrophages encircling blood vessels. The lesion was surrounded by reactive astrocytes. In addition, sections of medulla showed a poorly defined area of demyelination in the median floor of the fourth ventricle, with preservation of the axons.

In animal E (which died within 3 days after beginning arginine butyrate), horizontal sections of the brainstem and cerebellum showed gray brown discoloration in the floor of the fourth ventricle. Microscopic examination showed symmetrical demyelinating lesions of this region. The lesions were well defined and localized to the dorsolateral aspect of the vagus nucleus, immediately ventral to the area postrema. Additionally, a minute unilateral area of spongy degeneration in the dentate nucleus was seen, as well as a relatively well-defined area of demyelination in the globus pallidus. No inflammatory reaction or phagocytic activity was observed in these lesions.

There were no neuropathologic changes noted elsewhere in either animal. Specifically, there was no evidence of intracranial hemorrhage, and the region of the central pons was normal. Pathologic evaluation was otherwise notable only for marked cachexia in animal C.

Other studies. To discern whether the neuropathologic changes observed with butyrate administration were more likely due to hyperosmolality alone rather than butyrate toxicity, we infused hypertonic solutions (without butyrate) into animal D. This animal developed obtundation after receiving 8 g/kg/d of sodium butyrate for a total of 3 days, and returned to his baseline neurologic status within 48 hours following discontinuation of the infusion (Table 2). In this experiment, the serum sodium concentration had reached 178 mEq/L, with a serum osmolality of 360 mOsm/L. Nine months later, an equivalent osmotic load (adjusted for weight) was administered to the same animal via continuous intravenous infusion using sodium chloride alone. This solution had a concentration of 3,044 mOsm/L, approximately 10-fold higher than isotonic saline. The animal tolerated this infusion, lasting 13 days, and a slightly more concentrated infusion (3,352 mOsm/L), lasting an additional 12 days, without difficulty. There was no significant change in serum osmolality, due to a marked increase in water consumption and urine output. A combination of glucose and sodium chloride was then administered at a concentration of 6,160 mOsm/L (20-fold more concentrated than isotonic saline). Within 18 hours, the animal developed obtundation, intractable seizures, and death. Serum osmolality before death was 511 mOsm/L, with a serum sodium concentration of 209 mEq/L, and glucose of 1,324 mg/dL. At autopsy, no gross or microscopic abnormalities in the brain could be identified (Fig 4B).

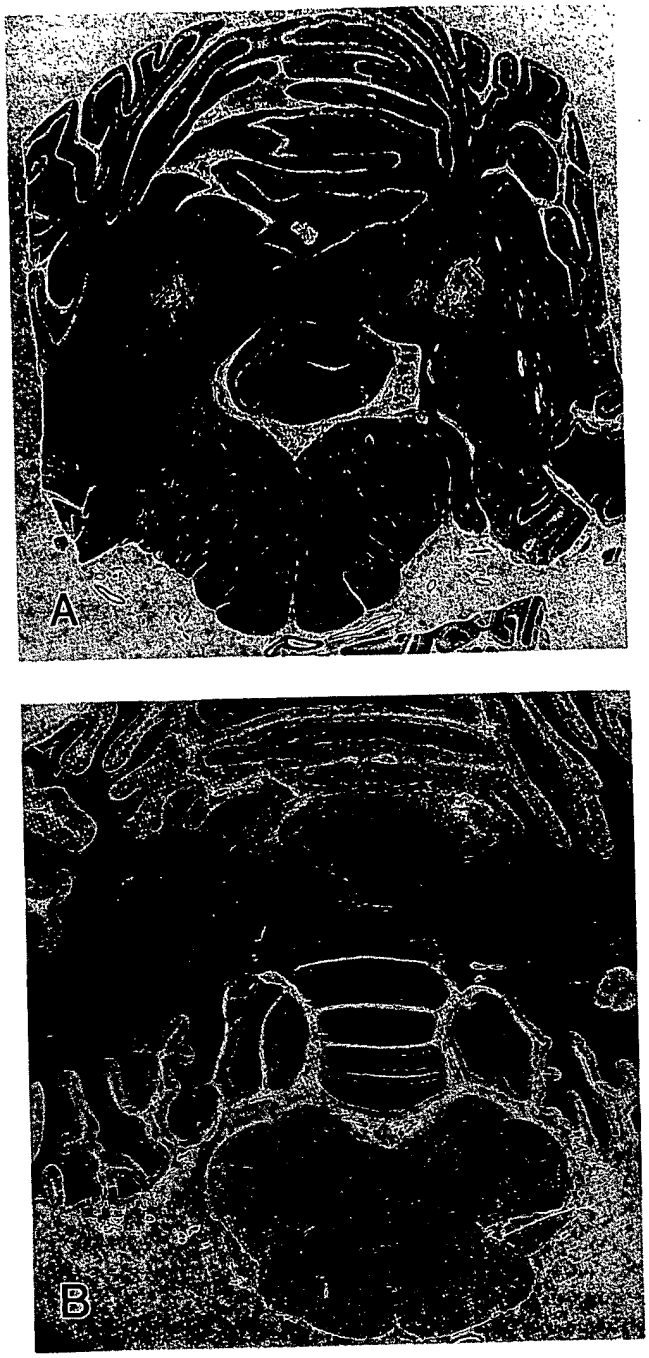

Fig 4. (A) Animal C. Horizontal section of the rostral medulla and cerebellum showing bilaterally symmetrical necrotic lesions in the dentate nuclei of the cerebellum (arrows). The lesions are partially cystic with increased vascularity and abundant macrophages. Luxol fast blue—Holmes' stain, original magnification ×4. (B) Corresponding section in control animal D, following death from hyperosmolality. No gross or microscopic abnormalities are identified.

DISCUSSION

A large body of evidence indicates that the presence of sufficient amounts of HbF can temper the clinical course of patients with sickle cell disease and β-thalassemia.[8-10] Thus, much attention is currently focused on the development of drugs that stimulate HbF production. Most known inducers of HbF, such as hydroxyurea and Epo, are thought to exert their effects indirectly by abruptly accelerating the rate at

which erythroid cells divide and mature.[11,12] In contrast, butyric acid induces the synthesis of HbF via direct effects on globin gene expression, largely independent of changes in cell cycling.[13,14] The mechanism for this effect has yet to be determined, although cis-acting sequences localized between −569 and −725 bp upstream of the chicken embryonic ρ-globin gene have been identified as necessary for butyrate inducibility in stably transfected mouse erythroleukemia (MEL) cells.[14] To estimate the potential therapeutic value of this class of drugs, we performed in vivo dose escalation studies, measuring HbF induction at each dose while continuously monitoring for, and carefully characterizing, toxicities. The results show that at doses of up to 3 g/kg/d, butyrate appears to be well tolerated and produces a 1.5- to 2.5-fold increase in HbF. Butyrate is a potent inducer of HbF when administered at high doses for prolonged periods of time. The HbF induction observed in these experiments should be magnified in circumstances of continuous erythroid stimulation and preferential F-cell survival, as occurs in hemoglobinopathies or β-thalassemia. Thus, doses required for the effective treatment of these disorders will likely be less than those used in our studies. A significant increase in fetal globin biosynthetic ratios has been noted in recent studies of arginine butyrate using doses between 0.5 and 1.5 g/kg/d in patients with sickle cell disease and β-thalassemia.[15] The additive effect observed when butyrate was administered in combination with Epo is similar to that described with other reported combinations of HbF inducers such as Epo (plus iron) and hydroxyurea.[16] HbF levels of 9% were achieved with this combination using a relatively nontoxic dose of butyrate (2 g/kg/d).

The level of HbF required for therapeutic benefit remains controversial. In a large prospective study of the natural history of sickle cell disease, Platt et al[17] found the frequency of painful crises to be inversely correlated with the square of the HbF level. Although there was no direct correlation between mortality and the percentage of HbF, the results suggest that even modest (threefold to fivefold) elevations in HbF may be of detectable therapeutic benefit. In contrast, a smaller prospective study by Powars et al,[18] identified "threshold" levels of HbF, below which no benefit was seen. In this study, an HbF level of greater than 10% was associated with a lower incidence of stroke or aseptic necrosis, and a level of greater than 20% was associated with fewer crises or pulmonary complications. Thus, whereas the definition of "clinically significant" increases in HbF production remains at best imprecise, there is evidence to support efforts to augment HbF to levels approaching 20%, while limiting toxicity. In the setting of preferential F-cell survival, or in combination with other inducers of HbF, it appears that with butyrate one may achieve this goal.

Butyrate has previously been evaluated in 10 to 14 day trials involving small numbers of patients with leukemia (at doses of 500 mg/kg/d),[19,20] and hemoglobinopathies (in doses up to 1.5 g/kg/d)[15] with minimal side effects. Thus, although it appears that these doses of butyrate are associated with little acute toxicity, there is as yet no experience regarding chronic toxicity. Predicting chronic toxicities is of obvious importance because patients with hemoglobinopathies will require long-term treatment, probably lasting many years. In an effort to characterize potential toxicities, we used doses in baboons 0.67- to 6.7-fold higher than used previously in humans. Our results may provide useful guidelines by which to develop protocols for future clinical trials involving butyrate. With one exception, short-term infusions of doses up to 4 g/kg/d were well tolerated. Laboratory evidence of hyperosmolality occurred with doses greater than 1 g/kg/d. Consistent with previous reports,[20] hypokalemia occurred with butyrate doses as low as 2 g/kg/d. Although the cause of hypokalemia in these animals is unclear, at times it occurred in concert with elevated serum bicarbonate levels, consistent with a metabolic alkalosis. Doses in excess of 4 g/kg/d were accompanied by decreases in reticulocyte, WBC, and platelet counts, and neurologic abnormalities including obtundation and cerebellar ataxia. An even higher dose (10 g/kg/d) produced fulminant multiorgan system failure and death. This is consistent with previous studies in rats, in which the maximal tolerated oral dose of sodium butyrate was 8.79 g/kg.[21] It is unclear whether the obtundation observed in four of the five animals resulted from hyperosmolality, butyrate, or both. As previously mentioned, there was one instance in which an animal's level of alertness improved with discontinuation of butyrate while hyperosmolality transiently worsened. Additionally, reports of poisoning associated with the illicit use of the butyrate analogue γ-hydroxybutyric acid,[22,23] describe manifestations similar to those we observed, including drowsiness and loss of consciousness.

Similarities in the neuropathologic changes observed in the two animals that died are striking. Both animals had focal pathologic changes within the dentate nuclei and floor of the fourth ventricle. Animal E also had changes within, but not strictly localized to, the globus pallidus. Although this complication may have been caused by factors other than butyrate (ie, hyperosmolality), similar lesions have not previously been described, despite a large body of literature concerning the neurologic complications of hyperosmolality. In fact, whereas intracranial hemorrhage is the most common manifestation associated with hyperosmolality,[24-27] and central pontine myelinolysis may occur during rapid correction of severe hyponatremia,[28] no such lesions were observed in our study. Intruigingly, receptors for the neurotransmitter γ ABA, have been found to be particularly abundant within the globus pallidus of baboons and the dentate nuclei in rabbits.[29] Finally, an animal that had previously developed reversible neurologic abnormalities while on butyrate tolerated butyrate-free solutions of equal or greater osmolality without difficulty for 25 days. This animal was then treated with a twofold greater solute load than had been administered with butyrate, resulting in a serum osmolality approximately 1.5-fold higher than had been achieved in any of the butyrate-treated animals. Death occurred but no neuropathologic changes were seen.

The current method required for butyrate administration (long-term continuous intravenous infusion) is impractical for broad application in clinical trials. However, the potent effect of butyrate on HbF induction holds promise for future investigations using more readily administered members of this class of compounds.

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